

The Interstellar Medium of Lens Galaxies

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Abstract. We use observations from the CASTLES survey of gravitational lenses to study extinction in 23 lens galaxies with $0 < z_l < 1$. The median differential extinction between lensed images is $\Delta E(B-V) = 0.05$ mag, and the directly measured extinctions agree with the amount needed to explain the differences between the statistics of radio and (optical) quasar lens surveys. We also measure the first extinction laws outside the local universe, including an $R_V = 7.2$ curve for a molecular cloud at $z_l = 0.68$ and an $R_V = 1.5$ curve for the dust in a redshift $z_l = 0.96$ elliptical galaxy.

1. Introduction

Extinction corrections are important for determining the Hubble Constant (e.g. Freedman et al. 1998), the cosmological model (e.g. Perlmutter et al. 1997, Riess et al. 1998, Falco, Kochanek, & Muñoz 1998), and the epoch of star formation (e.g. Madau, Pozzetti, & Dickinson 1998), but detailed studies of extinction are limited to nearby galaxies where individual stars can be observed. At larger distances, one must rely on studies of the spectral energy distribution of stars mixed with dust in an uncertain geometry. Gravitational lensing eliminates this uncertainty by using multiple lines of sight through a galaxy to the same background source. Thus, lensing is a powerful tool to measure the extinction properties of galaxies at moderate redshift.

The variation of absorption, A_λ , as a function of wavelength is described by the extinction law R_λ where $A_\lambda = R_\lambda E(B-V)$. Galactic extinction laws are well modeled by parametrized functions of R_V , where we have used the Cardelli et al. (1989) models. The typical Galactic value is $R_V = 3.1$, but the overall range is $2.2 \lesssim R_V \lesssim 5.8$. The value of R_V depends on the size and composition of the dust along the line of sight, and in the SMC and some regions of the LMC

the UV extinction curves show large deviations from the Galactic models. The properties of local dust are reviewed by Mathis (1990).

We consider here the multiply-imaged quasars observed for the Center for Astrophysics/Arizona Space Telescope Lens Survey (CASTLES, see Falco et al. 1999b), combined with archival HST data. Our initial survey of extinction in 23 lenses, 8 of which were radio selected, is discussed by Falco et al. (1999a).

2. Method

We measure the differential extinction between lines of sight in a gravitational lens by measuring the difference in color between the several images in the lens. In our analysis we make a number of simplifying assumptions: (1) the magnification is wavelength independent; (2) the magnification is time independent; (3) the source spectrum is time independent and (4) the extinction law is identical along the various lines of sight. Then the magnitude difference between images i and j is

$$m_i(\lambda) - m_j(\lambda) = -2.5 \log \frac{M_i}{M_j} + \Delta E_{ij} R\left(\frac{\lambda}{1+z_l}\right), \quad (1)$$

which depends only on the magnification ratio, M_i/M_j , the extinction difference between the two lines of sight, ΔE_{ij} , and the extinction law $R(\lambda/(1+z_l))$ in the lens rest frame. This dependence of the magnitude difference on extinction was first explored by Nadeau et al. (1991).

3. Results

We initially determine values for ΔE_{ij} by assuming a standard Galactic $R_V = 3.1$ extinction curve and then fitting the image magnitude differences as a function of wavelength for each lens. Figure 1 shows the distribution of differential extinctions for both early and late type galaxies. Most lens galaxies are early type galaxies, but the two lenses with the highest differential extinction, PKS 1830-211 and B 0218+357, are both late type galaxies where one of the lensed images lies behind a molecular cloud (Menten & Reid 1996; Frye et al. 1997). In both cases, we find dust-to-gas ratios a factor of 2–5 below standard estimates. The median differential extinction is $\Delta E(B-V) = 0.04$ mag for optically selected lenses and 0.06 mag for radio-selected lenses. This difference is not surprising, as we expect a bias against dusty lenses in optically selected samples.

We can determine the total extinctions only by using a model for the intrinsic spectra of quasars. While we can determine differential extinctions with an accuracy of ~ 0.02 mag, we can measure total extinctions only with an accuracy of ~ 0.1 mag. Formally we find that the median total extinction of the bluest images is $E(B-V) = 0.08$ mag. This matches the mean extinction of $E(B-V) = 0.10 \pm 0.08$ mag required to explain the differences between the statistics of radio and optically selected lens samples (Falco et al. 1998). Extinctions at the level of $E(B-V) \sim 0.1$ mag lead to significant corrections to the statistics of optically selected lenses, and must be included when using optically selected samples to determine the cosmological model.

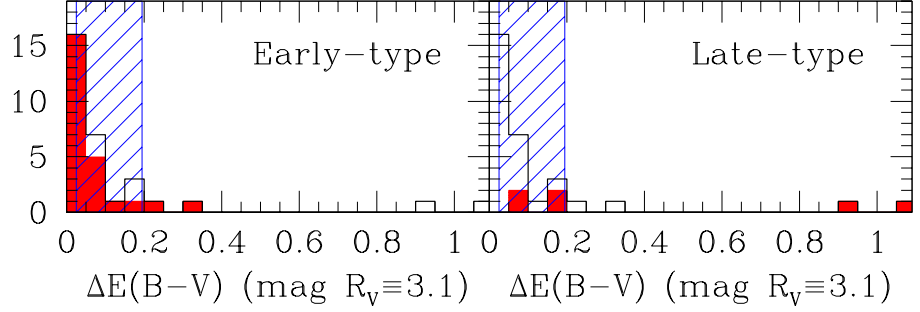


Figure 1. Histograms of the differential extinction in early type (left, shaded) and late type (right, shaded) lens galaxies. The superposed unshaded histogram shows the total distribution. The hatched region shows the extinction range estimated from a comparison of the statistics of optically-selected and radio-selected lenses by Falco et al. (1998).

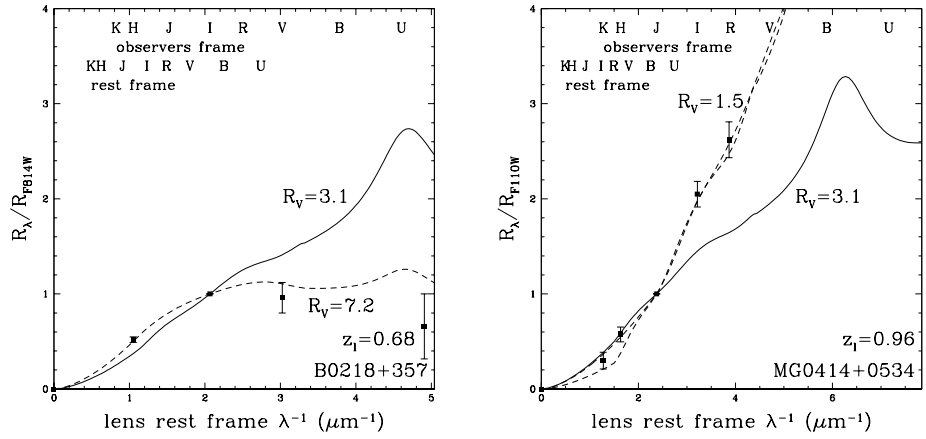


Figure 2. Extinction curves for B 0218+357 and MG 0414+0534. The solid line shows the standard $R_V = 3.1$ curve and the dashed line shows the best fit parametric curve. For simplicity the curves are normalized by the R_λ value of the filter closest to the lens rest frame V band. Both lensed sources are radio emitters and include a point at $\lambda^{-1} = 0$, allowing an absolute determination of both the extinction and the extinction curve.

Of the 23 systems considered here, 12 have adequate data to estimate both ΔE and R_V . Of these, 7 are consistent with the Galactic value of $R_V=3.1$, and the remaining 5 have values ranging from 1.5 and 7.2. Figure 2 shows the extinction curve derived for the two extreme cases. In B0218+357, a $z = 0.68$ late-type galaxy where one image passes through a molecular cloud, we find a very high value of $R_V = 7.2$. This is similar to the Galaxy where high values of R_V are associated with denser regions of the ISM. In MG0414+534, a $z = 0.96$ elliptical, we find $R_V = 1.5$.

While we see dust in lenses, our overall results rule out the “dusty lens” hypothesis of Malhotra et al. (1997). With high resolution imaging we now see that most very red lenses are dominated by emission from the lensed images of the host galaxy of the quasar or AGN. For example, the infrared images of MG1131+0456 are dominated by an extraordinarily bright Einstein ring image of the host whose properties can be used to prove that the lens galaxy is essentially transparent with $E(B-V) \lesssim 0.05$ mag (Kochanek et al. 1999).

Our basic CASTLES survey was not designed to study extinction laws, but we have begun to obtain detailed IR to UV HST photometry of the lenses with significant dust to make the first detailed survey of dust properties outside the Local Group. The new data will both greatly expand the wavelength coverage and minimize the effects of time variability on the results by obtaining all the data at one epoch.

Acknowledgments: Support for the CASTLES project was provided by NASA through grant numbers GO-7495 and GO-7887 from the Space Telescope Science Institute which is operated by the Association of Universities for Research in Astronomy, Inc. under NASA contract NAS 5-26555.

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